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THE GENERAL HYDROGRAPHY OF THE RED SEA

BY

E. F. THOMPSON, M.Sc.(N.Z.), PH.D.(CANTAB.)

WITH TWELVE TEXT-FIGURES

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THE GENERAL HYDROGRAPHY OF THE RED SEA

BY

E. F. THOMPSON, M.Sc.(N.Z.), Ph.D.(Cantab.)

WITH TWELVE TEXT-FIGURES.

A considerable amount of hydrographic work has been done in the Red Sea ; but up to the time of the John Murray Expedition only two extensive series of observations had been published. Over a number of years the Italian Research Ship " Magnaghi " (Picotti and Vercelli, 1927) made a great many hydrographic observations in different parts of the Red Sea ; tide stations were established and current observations made in the Straits of Bab-el-Mandeb (Vercelli, 1930). In 1929 the Dutch " Snellius " Expedition (van Riel, 1932) worked three stations in the Red Sea itself, and one on the shallow ridge of the Straits of Bab-el-Mandeb. From the data they drew a section, but offered no explanation of the characteristic distribution. A discussion of the Red Sea circulation is given by Krummel, II, pp. 685–687 (1911). He recognizes a cross and horizontal circulation in the winter months, but assumes that the summer circulation is the same as that for the winter (see also Schott, 1929).

Much information as to the local currents and winds is given in the " Pilot " for the Gulf of Aden and the Red Sea, but as the information there recorded is so often concerned with very temporary and local conditions, it has been used here more as a check on the deductions from other data than as original information. Currents with a velocity of up to 3 knots are met with, expecially in the southern part of the Sea. Many of the apparently contradictory reports of the currents observed are probably to be explained as due to the counter currents and anticyclonic eddies which are to be expected along the left-hand edge of such strong surface currents (Rossby, 1936, and Spilhaus, 1937).

The Egyptian Government have recently been engaged in hydrographic work, more particularly in the northern end of the Red Sea. Through the courtesy of their workers I have been enabled to see some of their unpublished material. In particular they have constructed a northern cross-section. As these results have not yet been published I have not actually used them in the present discussion ; but it is satisfactory to note that

they provide excellent corroboration of the conceptions here recorded and which were deduced before this information was available.

PHYSICAL CHARACTERISTICS OF THE AREA AND GENERAL DISCUSSION.

The Red Sea is a trough-shaped stretch of water about 1000 miles long, extending from the Sinai Peninsula to a few miles north of the Island of Perim. The average width is about 150 miles, and while the edges tend to be shallow and reef-bound, outside these the general depth is about 700 metres. The bottom is very irregular, and though depths of over 2000 metres occur in several places, it would seem that these great depths must be so isolated by submarine ridges as to be difficult to consider in anything but a very detailed study of this area. As will be seen later, the water below about 500 metres is so uniform in character that detailed consideration would seem unprofitable at this stage.

The climatic conditions need little discussion here. They favour a higher rate of evaporation than the average for this latitude. The rainfall is very small and a large amount of water is lost every year by evaporation and, as no large rivers find an outlet into the Red Sea, this loss has to be replaced by an inflow of water from the Gulf of Aden over the shallow sill near the Hanish Islands. In the rest of this account this shallow sill is referred to as the " Sill ". There is no doubt that it marks the southern hydrographic limit of this area.

Water movements in the Red Sea are due to four causes : tides, winds, change of density and loss by evaporation. Of these, the most important are those produced by the winds, and these are the only ones which will be considered in any completeness here.

The wind systems in the Red Sea are comparatively simple. For half the year, from May to September, the winds blow almost directly down the length of the sea from the Sinai Peninsula to the Straits of Bab-el-Mandeb (*i. e.* from the NNW.). For the other half of the year (October to April) the winds from the Sinai Peninsula to about latitude 22° or 21° N. remain unchanged, but south of latitude 20° N. the wind direction is, on the average, completely reversed, now blowing up the Red Sea, *i. e.* from a SSE. direction. There is considerable fluctuation in the direction and force, but it has been shown (Fjeldstad, 1930) that the total transport of water can be derived from the wind resultant.

Let us consider the effects of such a wind system. Several workers, notably Ekman (1922, 1927, and 1928), have shown that in a homogeneous water, a steady wind will produce the following water movements :

(1) " A pure drift current," limited to the upper layers, in which the surface water moves at 45° *cum sole* from the direction of the wind ; with increasing depth this deflection from the wind's direction also increases, while the velocity of the current decreases until it becomes negligible at the " level of frictional resistance ". The result is a net transport of water at 90° *cum sole* from the direction of the wind.

(2) " A slope current," producing by the piling up of the water along the coasts by the pure drift current. Such a current runs with uniform velocity and direction from the surface to the " lower depth of frictional resistance ", and is directed at right angles, *cum sole* from the direction of the slope.

(3) " A bottom current," part of the slope current, reaching from the " lower depth of frictional resistance " to the bottom, and turning *contra solem*, with increasing depth.

Ekman extended his consideration to cases where the depth was less than D (the

depth of frictional resistance), and where a coast-line interfered with the free movement of the wind current. He showed that in these cases the current would tend to move in the direction of the wind instead of to the right of it.

Some simple theoretical deductions have been made by Sverdrup (1933) in a consideration of such systems. It is sufficient here to state that certain factors, neglected by Ekman, tend to reduce the angle between the wind and the pure drift current, so that such a current has actually a component in the direction of the wind as well as at 90° *cum sole* from it; and further, that there seems to be considerable doubt as to whether a " slope current ", in the sense in which this term is used by Ekman, is ever found in a non-homogeneous medium such as the sea. Such is the general system of water movements, which, according to Ekman, are produced by a wind in a homogeneous body of water.

Montgomery (1938), in discussing the conclusions of Palmen (1932), states: " Along a deep coast-line, a normal drift current is set up with its transport cross-wind; a longitudinal wind produces ' Windstau ' of stream-effect type which sets up a gradient current. Along a very shallow coast-line frictional forces entirely outweigh the Coriolis force; the drift current is down-wind and a gradient current cannot exist. At intermediate depth, being the normal case, both types of ' Windstau ' occur simultaneously, etc." Off the coasts of the Red Sea the water is generally of " intermediate depth ", where the Coriolis force will be partly but not entirely outweighed by frictional forces.

We may take it, then, that the effect of a wind will be to cause a transport of surface and subsurface water to the right of the direction of the wind, and also, to a lesser extent, in the direction of the wind. In a narrow area such as the Red Sea, the importance of the second component will be relatively much increased, and considerable water transport will take place in the direction of the wind. At the same time the component at 90° from the direction of the wind will produce a piling-up of surface water against one coast of the Red Sea, such a piling-up being, to some extent, balanced by a bottom current in the opposite direction; thus a combination of water movements will tend to produce a solenoid field in the sense of Bjerknes (Bjerknes, 1911; Bjerknes and Sandström, 1910), causing movement of the water mass in the direction of the wind.

The net results, then, of a wind blowing from NNW. down the Red Sea should be:

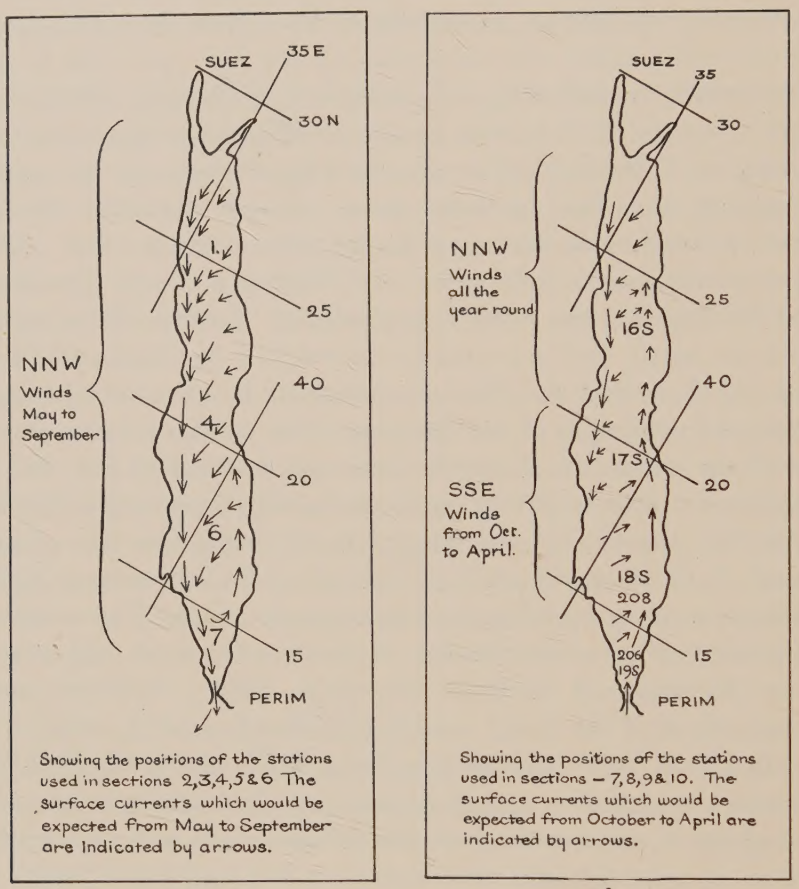
(1) A clockwise circulation in a vertical plane at right angles to the direction of the wind, with a piling-up of surface water on the African coast and an upwelling of deeper water moving in an easterly direction with a more or less stationary " cell " between these two movements (*cf.* Sverdrup, 1938).

(2) A movement of water, most pronounced in the surface layers, in the direction of the wind (*i.e.* parallel to the coast), this movement being the combined effect of the component of the pure wind current in this direction, the accumulation of surface water against the coast, and the extent to which the Coriolis force is overcome by frictional forces.

For the SSE. wind, blowing up the Red Sea, the phenomena will be exactly the same, but the direction of transport and trajectory will be in the opposite direction.

From this discussion it can be seen that for half the year, from May to September, the wind system will produce a clockwise circulation in a vertical plane at right angles to the direction of the wind, light surface water being transported to the Egyptian or western shore, and deep heavy water tending to well up on the Arabian or eastern shore.

At the same time there will be a movement, chiefly confined to the surface layers, in the direction of the wind, that is towards the Straits of Bab-el-Mandeb, and thus a current of surface water flowing out of the Red Sea. But the exit from the Red Sea is narrow and shallow, so that surface water will be piled-up in the southern end of the Red Sea, just north of these straits. This piling-up of surface water will produce a sinking of surface water at the place where it accumulates, together with a corresponding upward movement of deep water in the northern part of the Red Sea, from which the surface water has been removed. The surface currents to be expected in this season of the year are shown in Text-fig. 1, *a*.



a *b*

TEXT-FIG. 1.

For the second half of the year, from October to April, the wind current system in the area north of 22° N. should be exactly the same as that described above ; but south of about latitude 20° N. the wind system is completely reversed, so that in this region the opposite effect is produced. In this southern portion the circulation, in a vertical plane at right angles to the wind's direction, will be in the opposite direction from that of the previous season. The movement of water in the direction of the wind will now be towards the NNW. with a piling up of the light surface water along the Arabian or eastern coast, and a clockwise movement of the deeper masses, with upwelling along the Egyptian side. At about 20° N. latitude there will thus be a tendency for two circulations in the vertical

plane at right angles to the long axis of the sea, to rotate in opposite directions; while surface water will be driven both from the north and from near the Straits of Bab-el-Mandeb and will pile up near this latitude. This will produce a sinking of surface water near this spot and a compensating upward movement just north of the "Sill".

According to the relative strength of the north- and south-going currents, along the west and east coast respectively, there will be a greater or less area of overlap at about 22°–25° N. latitude, in which both the north and south and east and west currents may be expected to appear. The surface currents to be expected in this season are shown in Text-fig. 1, *b*.

The current entering the Red Sea from the narrows at Bab-el-Mandeb during the winter months is sufficiently rapid to have at least some of the characteristics of a Wake Stream, and will therefore, according to the conclusions of Rossby (1936), produce counter-currents consisting largely of anticyclonic eddies. The data at present available is not sufficient for a discussion of this aspect, but the erratic nature of the navigational records suggests that such a phenomenon is present.

From Vercelli's data (1930) it can be seen that in the extreme north of the Red Sea the surface water is cooled from September onwards, till the minimum temperature is reached in February (18·1° C.). As we move south, the average annual temperature change, both of the air and the surface water, decreases rapidly. Such a state of affairs will greatly increase the density of the surface water in the most northern part of the Red Sea (by 1·76 σ_t units). As the corresponding change in the southern portion is only about 0·46 σ_t units, it is to be expected that there will be a steady sinking of surface and subsurface water in the extreme north during the winter season. This effect will begin in late September, but will not reach its maximum effect till February, and will not seriously slacken till June. It is important to realize that this season of sinking does not entirely coincide with the winter wind season. Such a sinking will have to be compensated by movements from the south, for the rainfall is negligible. This compensating flow probably occurs chiefly along the Arabian coast.

Such, then, is the circulation which, on theoretical grounds, would be anticipated; each system will have reached its maximum development at the beginning of the opposite season, *i.e.* in October and May.

It will be realized that the longitudinal water movements in the Red Sea, piling up surface water near the Southern Sill in summer, and near latitude 21° N. in the winter, will produce high sea surfaces at these points in their respective seasons, and such elevations will appear in the dynamic picture of the surface. It is obvious, however, from the nature of the forces producing these surface deformities that Bjerknes' circulation theorem cannot be applied to these longitudinal sections. In fact, movements as calculated from dynamic topography will in many cases be exactly opposite to those actually known to occur from navigational observations.

CONSIDERATION OF DATA.

The data used in the construction of the following sections has been taken from the results of the John Murray Expedition (1933–34) and the "Snellius" Expedition (1929) (Van Riel, 1932). Curves have been drawn for the distribution with depth of salinity,

temperature, oxygen and density, and for the salinity-temperature correlation. The curves have been somewhat smoothed by reference to the density curves according to the procedure of Helland-Hansen (1916) and Helland-Hansen and Nansen (1926), and the figures for the sections have been taken from the smoothed curves.

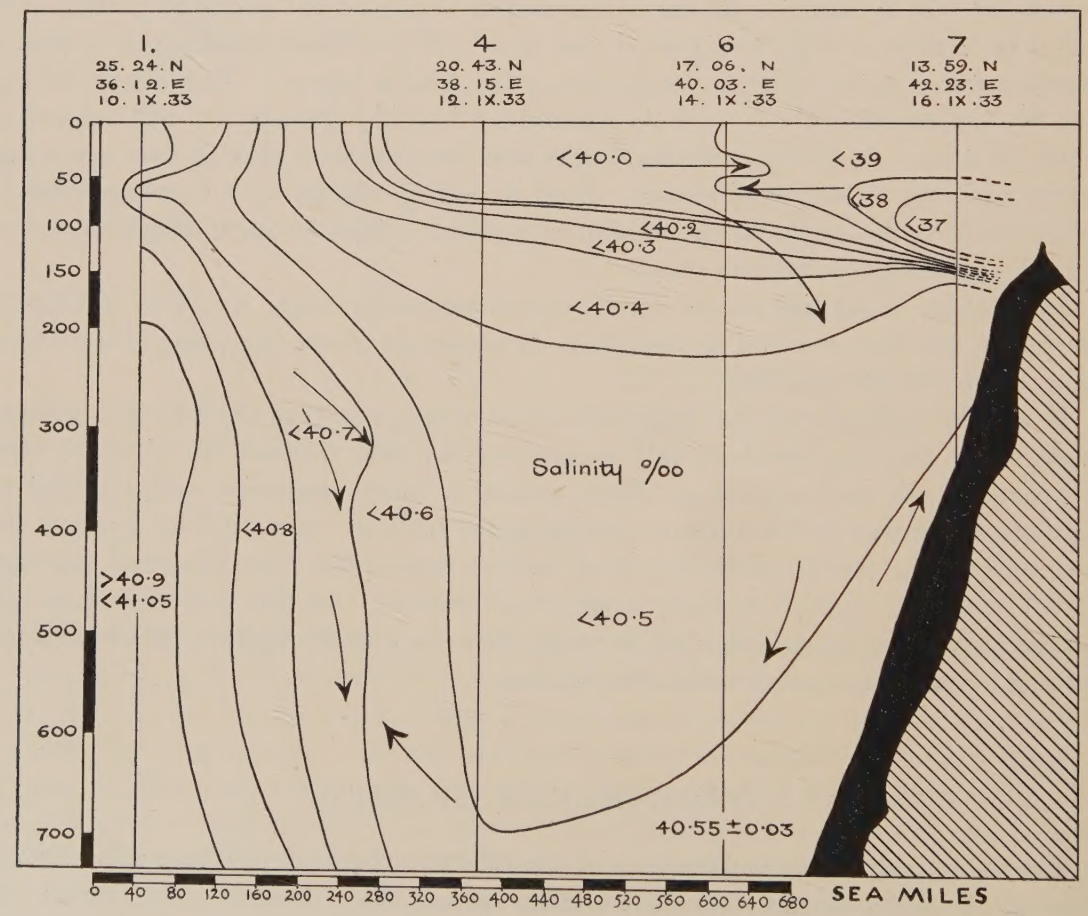
It should be pointed out that the stations used are several hundred miles apart and that the vertical scale is about 1800 times as large as the horizontal one.

Stabilities are usually quoted as $\frac{\Delta\sigma_t}{\Delta \text{ depth}} \cdot 10^3$.

RED SEA AT THE END OF THE SUMMER SEASON (MAY TO SEPTEMBER).

The Distribution of Salinity in September.

In Text-fig. 2 at Station 1 the southward bend of the isohalines down to 30 metres indicates the movement of high salinity surface water from the northern portion of the region under the influence of the NNW. wind. The depth to which active wind transport is indicated agrees well with the depth at which maximum stability is found (35 metres). This movement is possible owing to the summer warming of this saline water, which is consequently relatively light. To understand this sudden bend in the opposite direction at about 50 metres it is necessary to realize that just south of Station 1 the movements



Text-fig. 2.

across the sea are here opposed to one another. Below 50 metres the highly saline water which sank in February and March is seen ; by now the sinking is at a minimum.

At Station 4 the salinity down to about 40 metres, the depth at which the discontinuity is found, indicates the approximate depth of active wind produced movements. Below 40 metres the steep density discontinuity is characterized by a rapid rise in salinity to about 80 metres. This depth represents the level to which active mixing can take place in the winter months, when owing to the cooling of the surface layer the discontinuity had sunk to this level. Below 80 metres, the salinity increases more slowly, so that the 40·4 isohaline is found at 180 metres and water with a salinity of over 40·5 $^{\circ}/_{\circ\circ}$ at 700 metres. Below this depth to the bottom the salinity change is so small, 0·03$^{\circ}/_{\circ\circ}$, that it seems unprofitable to discuss it here.

The surface water at Station 6 consists of water with a salinity $<39^{\circ}/_{\circ\circ}$. This is largely a relic of the surface water driven into the Red Sea from the Gulf of Aden by the winter winds, though perhaps a small portion of it may be derived from the deeper Gulf of Aden Stream. Below this surface layer the arrangement of the isohalines is quite comparable with those at Station 4, but here the sinking, which was predicted on theoretical grounds, is indicated by the consistently lower level of all the isohalines above 40·3$^{\circ}/_{\circ\circ}$.

At Station 7 the water down to 40 metres is continuous with the surface water at Station 6 ; but below this level we see a much less saline body of water with a nucleus of salinity $<37^{\circ}/_{\circ\circ}$. This low salinity water, inserted between water masses of much higher salinity, is coming in from the Gulf of Aden as a current to compensate for the surface loss from the Red Sea. The upper boundary of this low salinity water in 40–50 metres is characterized by an extraordinarily high stability, the value of $\frac{\Delta\sigma_t}{\Delta \text{ depth}} \cdot 10^3$ being 160. It would seem impossible for much vertical mixing to take place across this extremely sharp discontinuity, and we must assume the major part of the assimilation takes place by horizontal mixing.

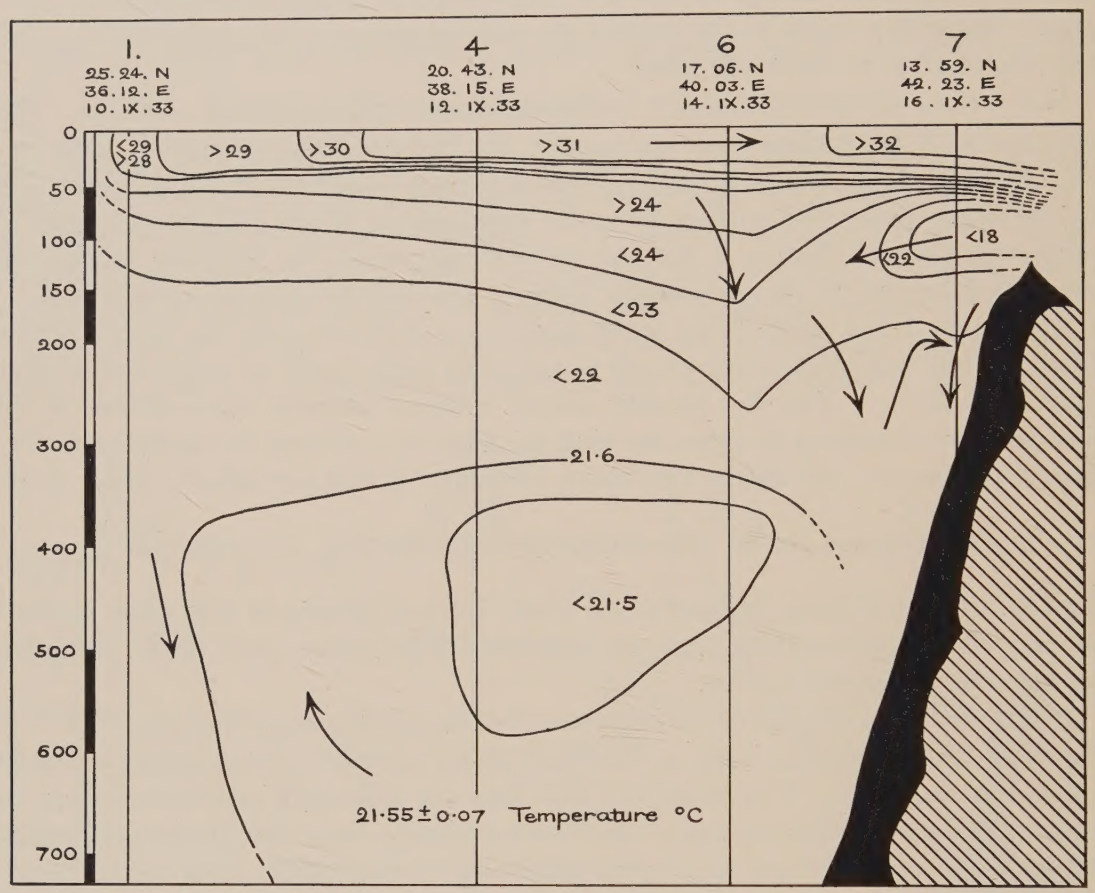
In general the section shows the outflow of Red Sea surface water over the " Sill ". The piling up of Red Sea surface water at Station 6 with a resultant down-pushing of the lower layers is well indicated. It is worthy of note that the downward component seems to be most marked between Stations 6 and 7, and this is probably due to the fact that the inflowing Gulf of Aden water really acts as a barrier additional to the " Sill ". The upturning of the 40·5 isohaline, which rises to 270 metres at the barrier, is probably due to the fact that the piling-up does not occur actually at the " Sill ". No doubt there is a slow creep of the deep Red Sea water up the slope to the " Sill ".

The Distribution of Temperature in September.

At Station 1 there is a fairly steep fall till 22° C. is reached at about 130 metres. Below this level the temperature falls very slightly to a minimum of 21·61° C. at 400, and then rises slowly to 21·84° C. at 1900 metres. The secondary rise is largely, though not entirely due to adiabatic heatings. This relatively low temperature (about 22° C.), together with the very high salinity ($>40^{\circ}/_{\circ\circ}$) clearly indicates the origin of this water. From the salinity it must have originated at the surface in the north of the Red Sea ; and from its low temperature it must have come from north of 26° N. latitude and have sunk during the months of February–April.

The temperature distribution at Station 4 requires little comment. It shows quite clearly the depth to which the wind current extends (about 40 metres). The subsequent slow rate of fall, the minimum at 400 metres and the great constancy of temperature below 150 metres are in complete agreement with the suggestions offered in the discussion of the salinity section.

At Station 6 a very marked down-bending of the lines occurs, so that the 22° isotherm is not reached till about 240 metres. This sinking of the lines of equal temperature indicates quite clearly an accumulation of surface water in the region, in good agreement



TEXT-FIG. 3.

with the isohalines of the previous section. At 400 metres a minimum (21·42° C.) is reached, but below 500 metres the same constant temperature is found as at Station 4.

Station 7 shows a further increase of surface temperature, while the upper boundary of the surface current is clearly indicated by the crowding of the isotherms between 40 and 60 metres. The inflow of subsurface Gulf of Aden water is clearly marked by a tongue of low temperature water, the nucleus of which, at about 70 metres, has a temperature below 18° C. Lower down the secondary rise of temperature indicates where we have again entered water of Red Sea origin.

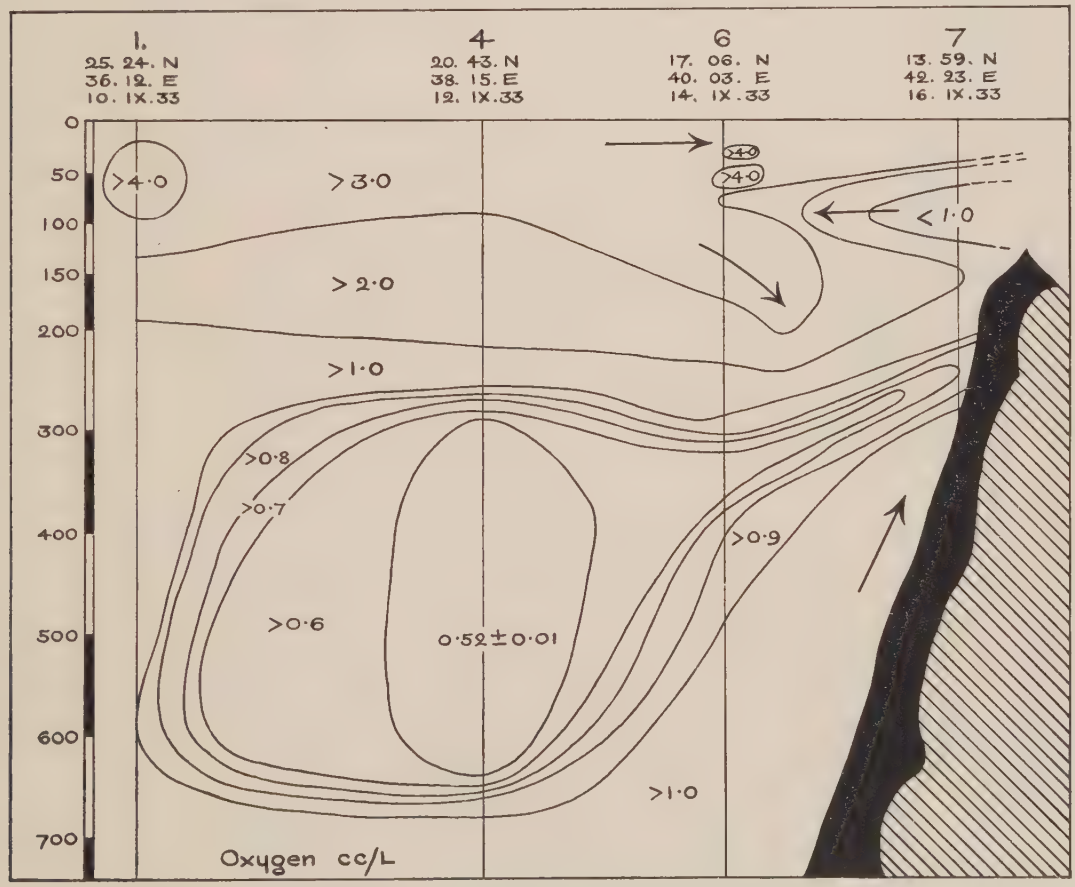
In general the section shows the same phenomena as were seen in the salinity section. There is strong indication of a piling-up and a consequent downward tendency of surface water between Stations 6 and 7. The intermediate temperature minimum at Station 7

is additional evidence of the existence of an influx of cold, low salinity water from the Gulf of Aden, below the warm high salinity outflow. The upward bend of the 22° C. isotherm between Stations 6 and 7 strongly suggests that there is at least some upward movement of the deep Red Sea water from the depths between the down-welling and the "Sill". The extraordinary constancy of the temperature below about 300 metres is quite in agreement with the very constant salinity found at all depths below this level. It emphasizes the fact that the sinking of the water in the northern part of the Red Sea can occur only during a very limited period, and suggests that the sinking is accompanied by considerable turbulence, producing complete mixing. A reference to the density section shows that this is in complete agreement with the modern view (Parr, 1938) that mixing occurs chiefly along the isosteric surfaces and not across them.

The Distribution of Oxygen in September.

At Station 1 the surface oxygen shows little significant variation down to nearly 100 metres; from there it falls rapidly to 3 c.c./l at 130 metres, 2 c.c./l at 190 metres, with a minimum of 1·0 c.c./l at 600 metres. From here there is a rapid though somewhat irregular rise, till at 1900 metres the oxygen content is 2·07 c.c./l.

At Station 4 the surface water has a concentration of up to 3·99 c.c./l, falling to 3 c.c./l at 90 metres and 2 c.c./l at about 200 metres. From here on the distribution with



Text-fig. 4.

depth falls very rapidly, so that at 300 metres it is only 0·53 c.c./l,and remains at this low value to below 600 metres. Below this depth the concentration rises rapidly to 2·04 c.c./l at 1500 metres.

Station 6 shows relatively high oxygen. The distribution shows considerable irregularity, which can no doubt be attributed to the fact that at this point there are two currents with very different characters moving in opposite directions. At this station there is a small portion of less than 3 c.c./l at 80 metres, which seems to be due to the effect of the Gulf of Aden stream. Apart from this small portion the concentration remains above 3 c.c./l till below 150 metres, and the 2 c.c./l line is not found till 230 metres, or 30 metres lower than at Station 4. When it is borne in mind that at this point the water is met by the Gulf of Aden stream the nucleus of which has an oxygen concentration of less than 0·6 c.c./l it is seen that the down-welling of the surface water must be a very well-defined movement. Below 250 metres the concentration drops rapidly to a minimum of 0·60 c.c./l at 300 metres. Thence it rises rapidly to 2·18 c.c./l at 800 metres, only to fall again to 1·09 c.c./l at 1000 metres.

At Station 7 we find surface water with a concentration over 3 c.c./l down to 40 metres. Thence it drops rapidly to a minimum of 0·57 c.c./l at 100 metres. Below this it rises rapidly to 2·12 c.c./l at 150 metres to fall again to 0·75 c.c./l at 250 metres.

The diagrams as a whole show the same evidence for a downward component between Stations 6 and 7, as was seen in the salinity and temperature diagrams. The minimum oxygen zone between 300 and 600 metres at Station 4 agrees well with the position of the temperature minimum ; and here, again, the thinning out of the mimimum oxygen zone in between Stations 6 and 7, and the upward curve of the lower 1 c.c./l line against the barrier indicates the same slight upward movement of deep water between the piling-up of surface water and the barrier, as was seen in the other two sections.

Except at Stations 6 and 7, the boundary of the wind-driven current is not well marked. This is due to a combination of physical and biological processes. In these clear waters Gilson (1937) has shown that active photosynthesis can continue down to about 160 metres, so that production of oxygen from this source would tend to obscure the depth of active surface mixing which must be confined to much shallower levels. The physical reason is to be found in the piling-up of surface water in this region (between Stations 1 and 4) during the winter months, the effect of which on the oxygen concentration is seen well below 150 metres.

The secondary rise of oxygen values at depths below 600 metres strongly suggests that the main mass of high salinity water sinking in winter from the northern end of the Red Sea falls to considerable depths relatively rapidly ; and that the low oxygen values at 350–550 metres represent a " cell ", fed only very slowly by water from greater depths.

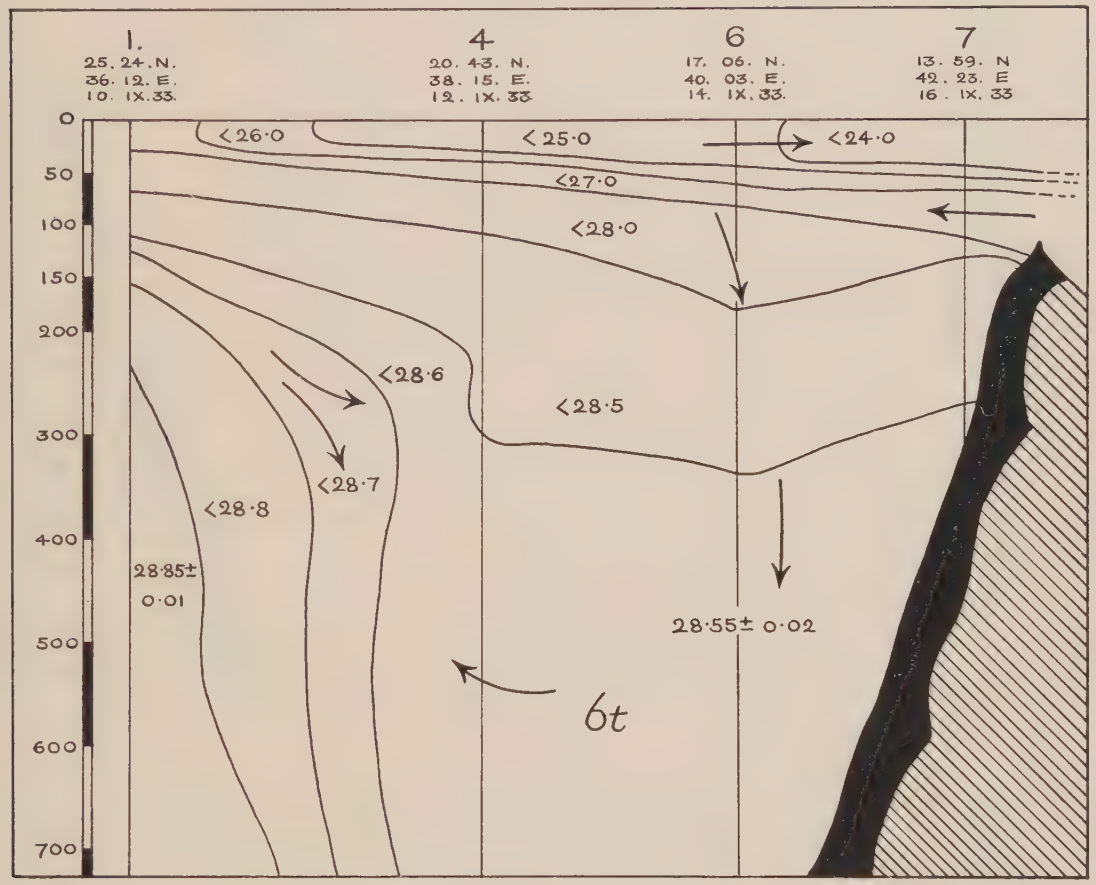
The subsurface inward movement of water from the Gulf of Aden, seen in the previous sections as a tongue with a low salinity and temperature, is here represented by a body of water with a low oxygen value. As it advances into the Red Sea, its concentration of oxygen is increased, chiefly by lateral mixing. The low initial oxygen concentration found in this water is an indication of " age ", not stagnation.

The Distribution of Density in September.

The distribution of density in this season supports much that has already been said in discussing the other sections. The bending of the isosteres below 100 metres between

Stations 4 and 1 indicates where the deeper dense water is overlaid by surface water from the eastern (Arabian) coast. The accumulation of surface water in the region of Station 6 and the tendency for water from the deeper layers to creep up immediately against the " Sill " are clearly seen in the course of the 28·0 and 28·5 isosteres.

At Station 1 density rises slowly to 28·86. If no allowance is made for adiabatic warming, there is a secondary minimum at 1900 metres, but when this allowance is made (Hesselberg and Sverdrup, 1914) and potential densities are used, this minimum disappears. The whole of the water south of Station 4 and below 300 metres shows very small positive or zero stability, and at about 400 metres at Stations 4 and 6 very small negative stabilities



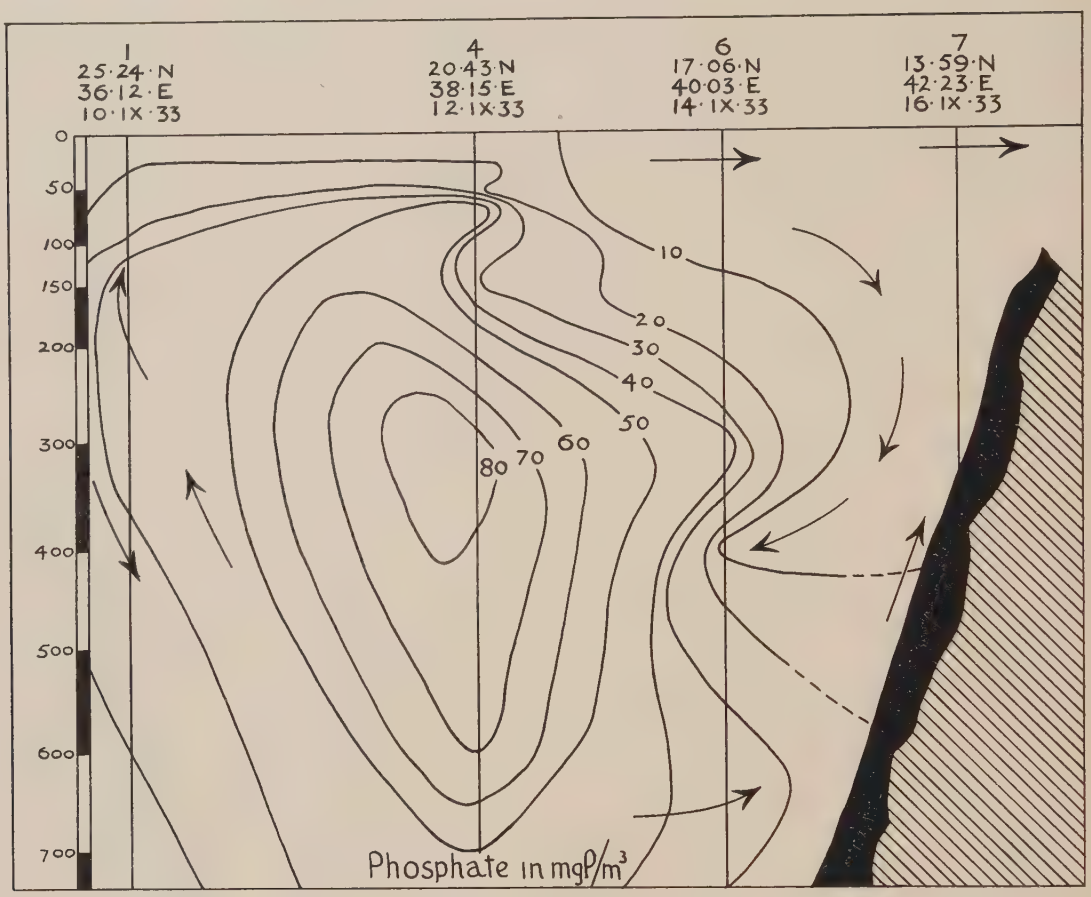
Text-fig. 5.

are found. The low stability in the deeper layers probably contribute largely to the great homogeneity of the deep bottom water.

The Distribution of Phosphate (mg.P/m³) in September.

There seems little need to describe the Stations in detail. In general Text-fig. 6 shows the same main features as the other sections. The steep downward sweep of the 10 mg. line is a very good indication of down-sinking from the surface of water which has been depleted of phosphate. At about 400 metres it shows a sudden in-turning suggestive of a circular movement in a clockwise direction, with the 80-mg. portion as the centre of the rotation. This 80 mg. part, the maximum value found, is at the same

position as the centre of the oxygen and temperature minima. Low oxygen, accompanied by high phosphate, is usually an indication of water which has for a long time been cut off from the surface and has not undergone any great mixing with other waters. As will be seen later, this is the case here.



Text-fig. 6.

RED SEA AT THE END OF THE WINTER SEASON (OCTOBER TO APRIL).

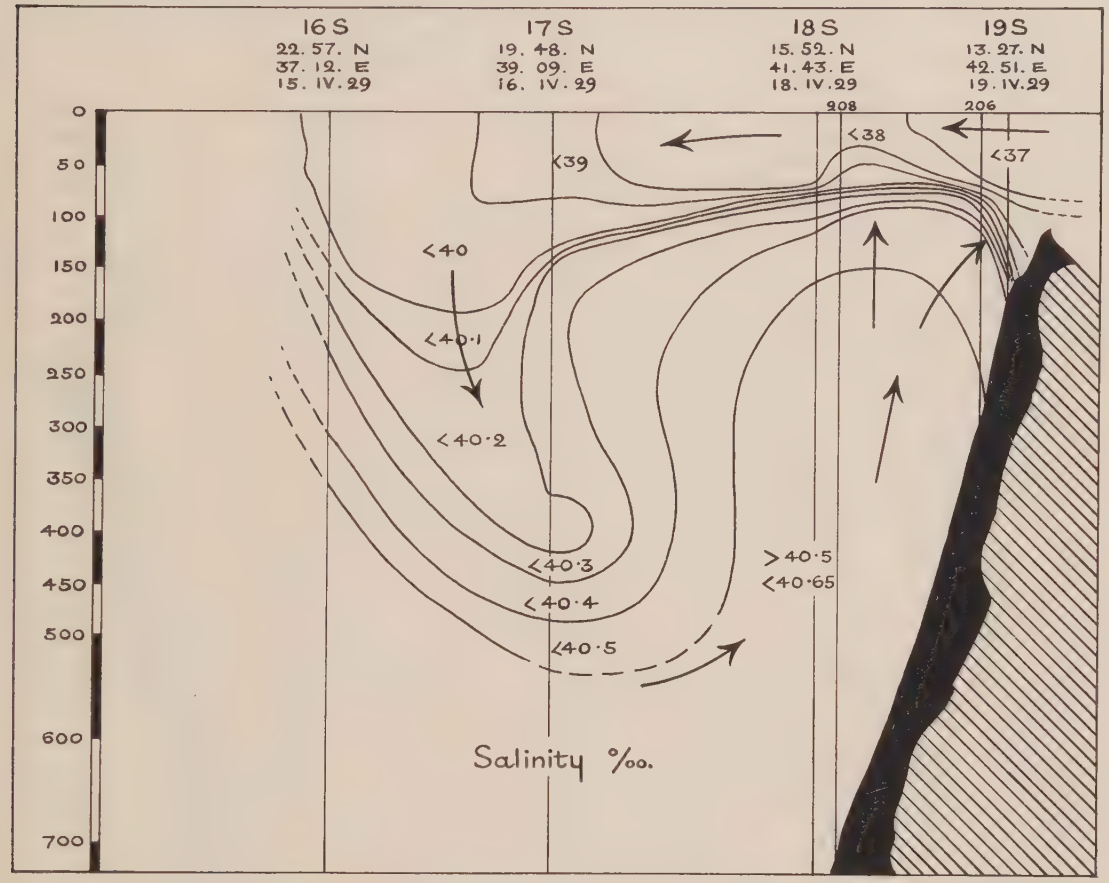
Of the stations used in the following sections, four, 16S, 17S, 18S and 19S, are from the "Snellius" Expedition (Van Riel, 1932), and were carried out in April, 1929. Stations 206 and 208 are from the John Murray Expedition (Sewell, 1936) and were carried out in the middle of May, 1934. It is unfortunate that we have to consider together stations that were carried out at such long intervals, but the paucity of the material is such as to allow of no alternative.

The Distribution of Salinity in April and May.

The main features of Text-fig. 7 are fairly obvious. There is clearly an inflow of fairly saline surface water from the Gulf of Aden. Such a current was predicted in view of the SSE. winds prevailing here at this season of the year. Reference to Text-fig. 1, *b* will show that this current transports water chiefly up the Arabian coast to between Stations 17S and 16S, and from there the water is carried across the sea towards the west (African)

shore. The accumulation of this surface water at about latitude 21° N. is clearly indicated by the trend of the isohalines in this position. The great depth to which this surface water affects the isohalines is probably to be explained by the low stability ruling in this region at this time of the year (Text-fig. 11), a condition which favours vertical mixing.

Such an accumulation of surface water, with its consequent pressure on the lower layers, must cause an equivalent upward movement of the deep water at some other locality. As this is the season when the very saline water from the extreme north is sinking to great depths, an upward movement of deep water cannot take place there.



Text-fig. 7.

It must occur near the " Sill " at the southern end of the Sea. That this is so is indicated by the lines marking off the water of salinity $>39^{\circ}/_{\circ\circ}$ in the region next the " Sill ". This interpretation is also supported by the salinity-temperature correlations. From the raised positions of the high salinity water next the " Sill " as compared with the condition in the summer season, it may be inferred that there is a far greater outflow of this deep Red Sea water at this time of year than in the previous season.

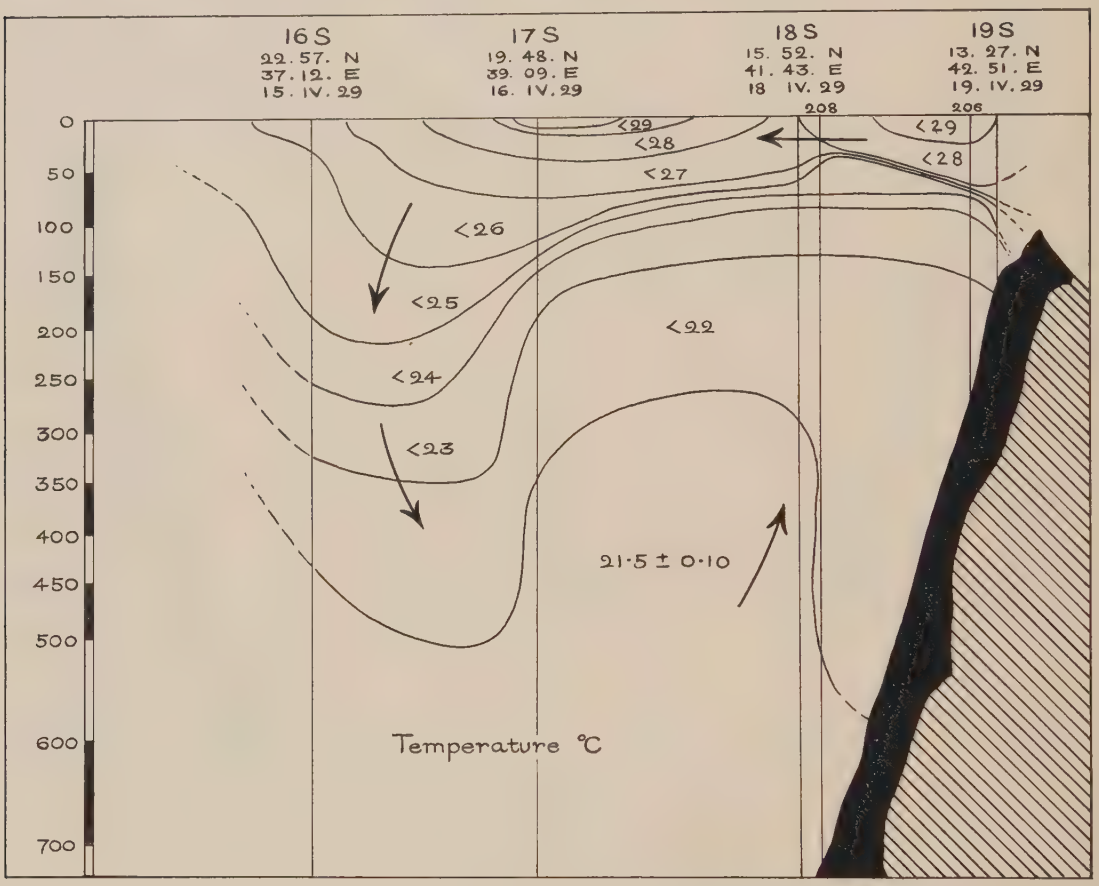
It is difficult to determine the depth of this inflowing surface current in the southern part of the sea. Reference to the stability curves (Text-fig. 11) shows that there is rather poor agreement between the " Snellius " and John Murray stations. This may be due to the difference in the years of observation, or perhaps to the internal waves known to occur in this region (Vercelli, 1927–1930 ; Schott, 1929). It may be estimated that the depth

of the inward movement in the region of Station 18S is about 80 metres. It is interesting to note that whereas in the summer the inflow from the Gulf of Aden consists of *sub-surface* water, the inflow is now confined to the *surface*, and the position of the summer sub-surface inflow is occupied by a highly saline bottom outflow.

The sinking of high salinity water from the north is indicated by the asymmetrical nature of the curves between Stations 16S and 17S.

The Distribution of Temperature in April and May.

Reference to Text-fig. 8 shows good indication of the wind-driven surface current entering from the Gulf of Aden and the piling-up of surface water at about 20° N. The



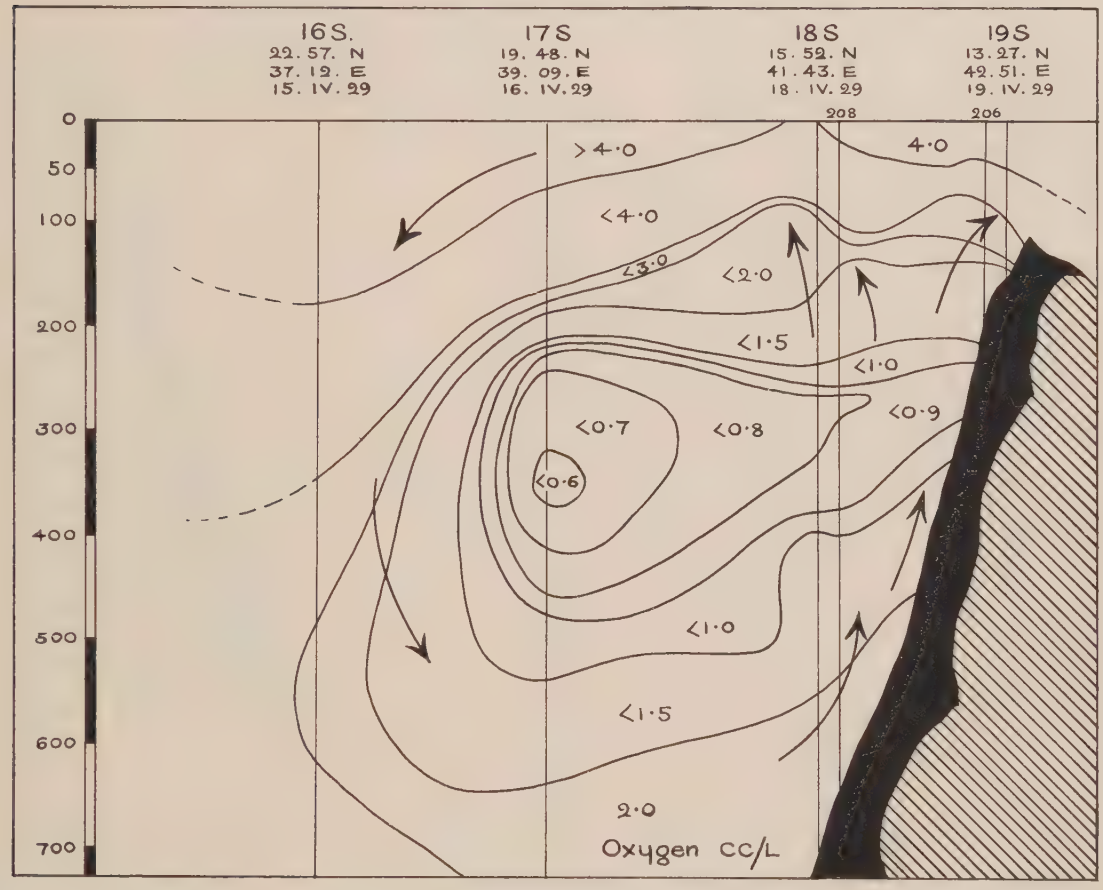
Text-fig. 8.

downward mixing of water in this region is strongly indicated by the downward bending of the isotherms. At Stations 18S, 208 to 206 and 19S there is also the same indication of an upward movement of deep Red Sea water as was seen in the salinity figure. The crowding of the isotherms round 27° between Stations 208 and 206 strongly supports the view that two different and opposed bodies of water are meeting here.

There is a suggestion of an eddy in the region of Station 18S. Such an eddy is to be expected on the left side of a fast-flowing current of this type (*cf.* Rossby, 1936), being part of the resulting counter current, which will consist largely of eddies.

The Distribution of Oxygen in April and May.

As in the salinity and temperature figures, so here, too, there is good evidence of a wind-driven current bringing in surface water from the Gulf of Aden and piling it up, with the resulting downward mixing in the region of 20° N. The low stability of the water here at this time would facilitate this downward mixing. That such a phenomenon occurs is clearly indicated by the sharp downward bending of the isolines. There is likewise indication of an upward movement at Station 19S, and at 206. It would seem that the " upwelling ", deep Red Sea water is split by the inflowing Gulf of Aden surface current,



Text-fig. 9.

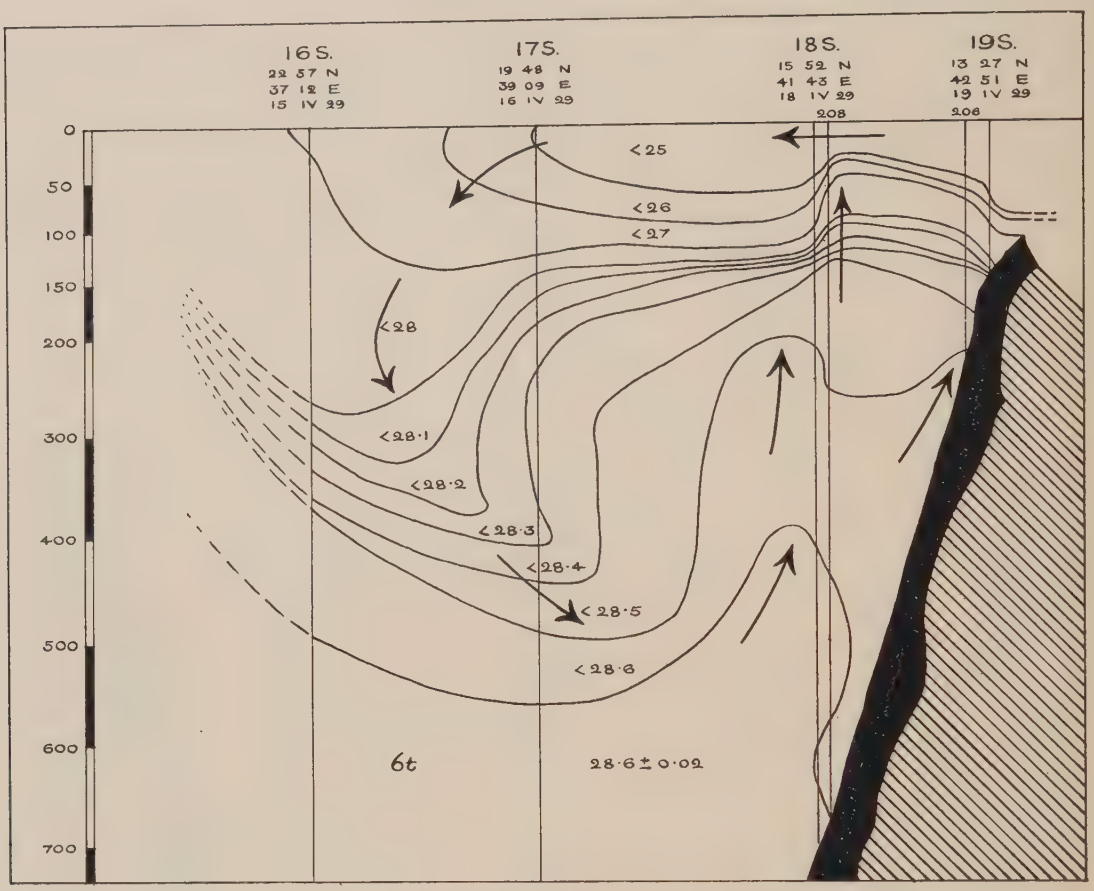
one part appearing at the barrier, the other being carried upwards and backwards and mixing with the surface current at Station 18S. This second portion of deep water, reaching the surface at Stations 18S and 208, is probably centred in the eddy to be expected here.

The relatively high oxygen concentration (>2·0 c.c./l) in the deepest northern waters also suggests that very saline water, coming from the region of the Gulf of Suez, is at this time sinking down and moving slowly southward.

An interesting feature of the figure is the appearance of an oxygen minimum, centred at Station 17S at about 350 metres. The recurrence of this phenomenon in approximately the same place as was found for the previous season is significant.

The Distribution of Density in April and May.

Here, again (Text-fig. 10), we find unmistakable signs of surface inflow from the Gulf of Aden, piling up and mixing with the lower layers in the region of 20° N., and of an upward tendency of deep water both toward Station 18S and near the " Sill ".

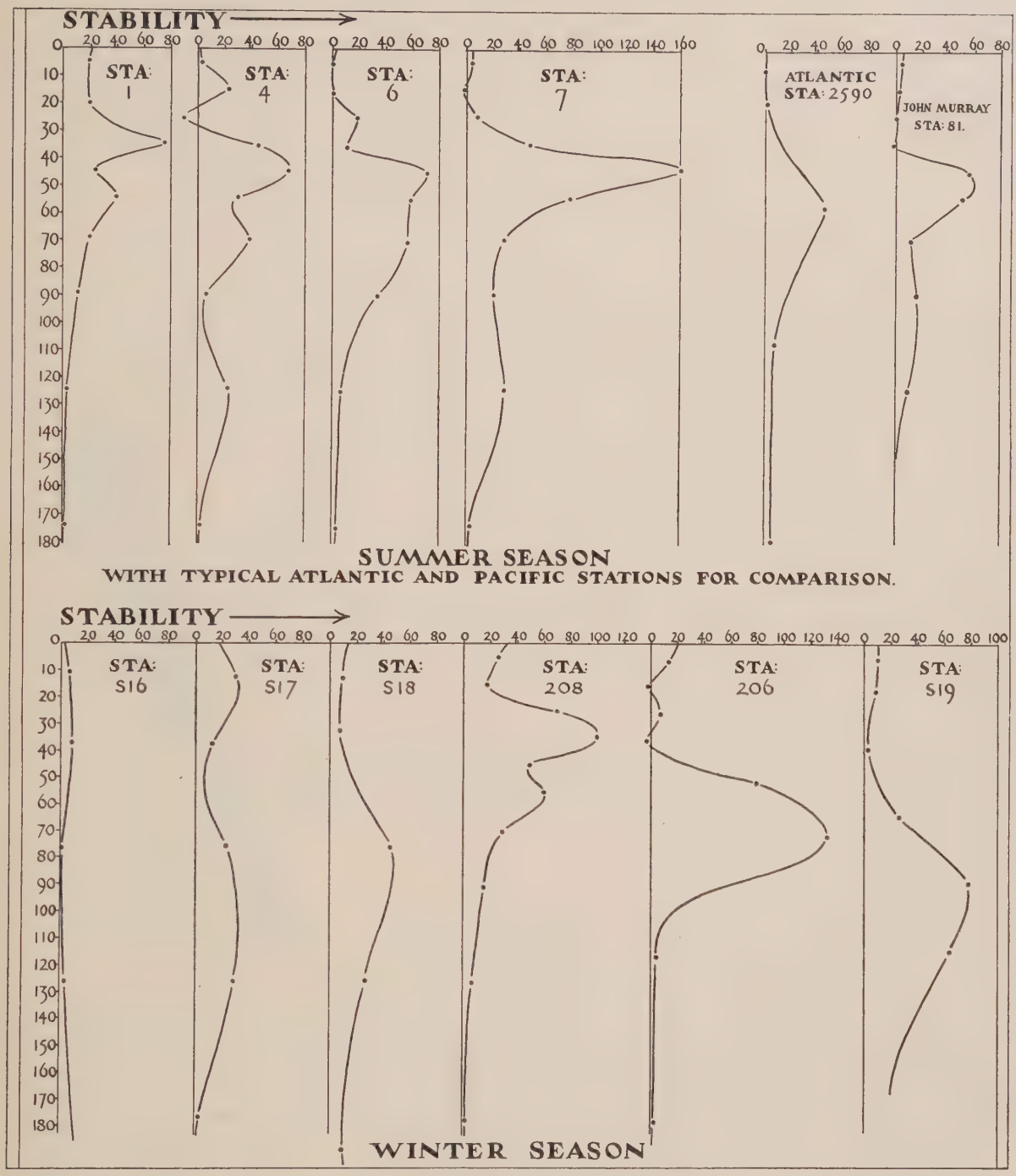


Text-fig. 10.

The Distribution of Density in the Winter and Summer Seasons.

Text-fig. 12 is merely a combination of Text-figs. 10 and 5. It shows quite clearly how, in the winter season, there is a piling-up of surface water and consequent downward mixing in the region of 20° N. latitude, with resulting upward movements near the barrier, whereas in the summer season the reverse is the case. The whole system appears to be pivoted about the position X on the figure. In this interpretation we find the explanation of the oxygen-poor, phosphate-rich water, already seen, for X is almost exactly the centre of this region. It is seen, then, that this central region of water is a pivot, on which the rest of the sea rotates in a vertical plane, so that as one looks at the figure the rotation is anti-clockwise in the winter, clockwise in the summer. This pivotal region is very nearly permanent in position. It is exposed but little to mixing and consequently has little opportunity for renewal of oxygen, or loss of phosphate. As a result, the former has been largely used up and the latter has greatly accumulated. By close examination of the salinity-temperature and salinity-oxygen correlations it can be shown that this cell,

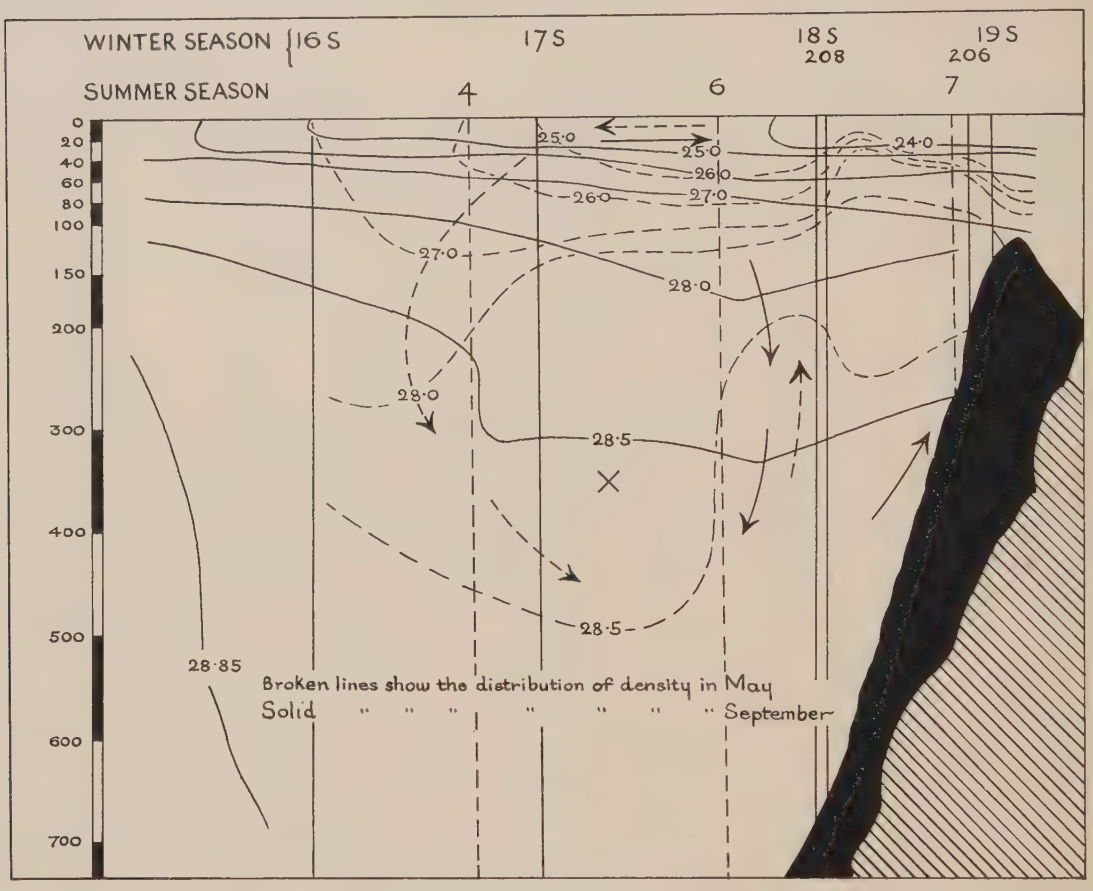
forming the pivot mass, is not absolutely cut off from outside supplies and mixing. During the winter it receives a supply of water of considerably higher oxygen concentration,



Text-fig. 11.

slightly higher temperature and rather lower salinity. The nature of the movements by which this cell is fed are not at present clear, but there is a suggestion that they are largely confined to the winter season and are, at least to some extent, dependent on seasonal changes in the circulation *across* the sea.

There is a slow sinking of very saline water from the north end of the Red Sea. The fundamental assumption that all waters have had their origin at the surface, or from mixtures of surface waters, leaves no other source for the water of salinity >40·0‰ and a temperature of 22± 0·5° C., which fills practically the whole Red Sea basin below 180 metres and is the most characteristic feature of the zone. As the original surface water must have had a temperature not much greater than 22° C., it is obvious from Vercelli's data (1930) that the sinking must occur from February to April and from north of 26° N. latitude. This is in entire agreement with the figures of the sections, and with the density



Text-fig. 12.

changes required by such a sinking. The longitudinal rotational movements are such that there will tend to be a far greater escape of this deep, highly saline water over the " Sill " in the winter than in the summer.

Additional confirmation of the vertical rotational movements in the northwest-southeast direction can be obtained from a consideration of the salinity-temperature correlations and their associated oxygen values. From these it can be seen that waters with the same T/S correlations as are found at 420 and 480 metres at Station 16S are found again at Station 18S at 250 and 350 metres respectively. Further, if the oxygen concentrations of these bodies of water with identical conservative characters (T/S) are compared, it is found that the values at Station 18S are about 1·1 c.c./l lower than at Station 16S. It seems reasonable that this lowering of the oxygen values, in passing from

north to south, can have taken place only by this deep water moving in that direction, for alteration due to internal mixing is ruled out by the constancy of the T/S correlations. The rise in the level of the water in passing from Station 16S to 18S is best explained on the rotational theory already stated. The movement of the water from Station 16S to Station 18S with the accompanying consumption of 1·1 c.c. O_2/l would then occur during the winter season (seven months).

In the opposite season (summer) the oxygen gradient for deep water masses between Stations 6 and 4 is reversed, supporting the conception of a reversal in the direction of rotation with the two seasons. The rate of oxygen consumption is of about the same magnitude as for the winter season.

The writer is not aware of any data on oxygen consumption at such levels (350–600 metres) in water with such a relatively high temperature (*circa* 22° C.). From the data available for the rate of oxygen consumption in the Atlantic it would seem not unreasonable to assume a consumption here of 2 c.c./l/year. This would agree with the suggested circulation and the results from the T/S correlations, which suggested that water moved from 420 metres at Station 16S to 250 metres at Station 18S in seven months during the winter, moving back again during the five months of the summer season. This would give the water at about 400 metres, south of 23° N. latitude, a winter velocity of slightly less than 2 miles per day, or 3·7 cm./sec., towards the SSE., and a summer velocity of slightly more than 2 miles per day in the opposite direction. Such a rate of flow is quite comparable with the rates of flow usually found under similar conditions.

Superimposed on this system are the rotational movements towards the Arabian and African coasts in a plane at right angles to the long axis of the sea, due to the *cum sole* component of the seasonal winds. In the northern part of the sea the movements have the same direction throughout the year, but south of latitude 22° N. there is a reversal with the change of season.

These conclusions are in complete agreement with all the data at present available. That such a simple circulation has not been previously elucidated is probably due to the fact that up to the time of the John Murray Expedition, satisfactory data for the summer season were not in existence.

SUMMARY.

1. The physical conditions of the area are analysed and the probable circulation to be expected is deduced. The hydrographic data are then discussed and shown to agree with the predicted circulation.

2. It is shown that the whole of the Red Sea below a depth of 200 metres is filled with water of extraordinarily constant temperature and salinity. From the properties of this water it is seen that it must originate at the surface in the Red Sea, north of latitude 26° N., and sink from there between late January and early April.

3. The upper layers of the sea are subject to a wind-system which changes with the two seasons.

In the summer water is transported down the whole length of the Red Sea, to pile-up near the " Sill " in the south and cause an outflow of the " jet " type through the Straits of Bab-el-Mandeb into the Gulf of Aden. Owing to the considerable stability now found here at 40–50 metres, active wind transport is confined to a layer of this depth, and mixing

must be largely horizontal, though vertical mixing will be found at the scene of the upwelling along the Arabian coast.

During the winter the wind system is such that the currents in the Red Sea south of latitude 20° N. are reversed, and there is a piling-up of surface water near that latitude. At the scene of this accumulation of surface water there is now relatively little stability in the upper layer, so that considerable vertical mixing can take place ; thus the effect of the surface accumulation is now felt to considerable depths. Lateral transport, south of latitude 20° N., is now towards the Arabian coast, where surface water accumulates. There will be a corresponding tendency for upwelling on the African coast.

4. The seasonal change in the surface current system tends to cause corresponding rotational movements in both longitudinal and transverse vertical planes. The centre of the longitudinal " vertical " rotation is situated at about 320 metres in 17° N. latitude. This centre, characterized by very low oxygen and high phosphate values, seems to be the centre of a fairly permanent " cell ". Below the cell, the seasonal winds induce seasonally alternating deep currents with a velocity of about 2 miles/day (3·7 cm./sec.). The oxygen consumption at about 400 metres seems to be of the order of 2 c.c./l/year.

5. It is shown that the seasonal alternations of the surface movements will alter the amount of deep Red Sea water flowing out over the " Sill ". The effect is such that the flow is at a minimum in the summer season.

6. During the summer the inflow from the Gulf of Aden is entirely subsurface, while in the winter the inflow is confined to the surface layers.

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